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PHILIP A. KESSEL

Date

Technical Advisor

Space and Missile Propulsion Division

Estimating the Initial Crack Size in a Particulate Composite Material: An Analytical and Experimental Approach

C. T. Liu
AFRL/PRSM
10 E. Saturn Blvd.
Edwards AFB CA 93524-7680

Abstract

In this study, a technique to predict the equivalent initial crack size (EICS) in a particulate composite material, containing hard particles embedded in a rubber matrix, was developed using constant strain rate crack propagation test data. The accuracy of the developed technique was determined. In addition, the statistical distribution of the equivalent initial crack size follows the second asymptotic distribution of maximum value.

Introduction

Reliable performance of a structure in critical application depends on assuring that the structure in service satisfies the conditions assumed in design and life prediction analyses. Reliability assurance requires the availability of nondestructive testing and evaluation (NDE) techniques to characterize discrete cracks according to their location, size, and orientation. This leads to an improved assessment of the potential criticality of individual flaws. To achieve this goal, an inspection criterion, regarding the size of the crack and the inspection interval, need to be developed. The inspection criterion should not be driven by inspection capability of NDE methods, but rather, selection of NDE methods should be driven by real engineering requirements.

It is well known in the aerospace industry that the initial crack sizes in metals and super alloys are too small to be detected by any NDE techniques. Consequently, the initial crack size in metals has been determined using experimental results, such as fractographic data or S-N data (1-2). From the experimental S-N data, one can determine the critical crack size at the time of failure. Then, the initial crack size is computed from the critical crack size by conducting the crack growth analysis backward. After determining the initial crack size, fatigue failure of aircraft or aerospace structural components can be predicted under any service loading spectra by carrying out the crack growth analysis.

While the basic concept for determining the initial crack size in particulate composite materials is similar to that for metallic materials used in aircraft industry, there are significant differences in the technical approach. This is because the crack growth behavior in particulate composite materials under constant strain rate loading is quite different from that in metals or super alloys subjected to cyclic fatigue loading. Therefore, it is the purpose of this study to develop a technique to predict the initial crack size in particulate composite materials.

In this study, the equivalent initial crack size (EICS) in a particulate composite material, containing hard particles embedded in a rubber matrix, was determined using constant strain rate

crack propagation test data. Uniaxial tensile specimens with and without pre-cracks were tested at a constant strain rate of 0.067 in/in/min. The experimental data were analyzed and the results are discussed.

Analytical Analysis

To determine the EICS, the following information is needed: (1) crack growth rate parameters, (2) critical stress intensity K_{IC} and threshold stress intensity factor K_{th} under which crack will not grow, and (3) time to failure data under constant strain rate. Crack growth rate parameters as well as K_{IC} and K_{th} are determined experimentally using pre-flawed specimens. Time to failure data are also obtained experimentally using specimens without a pre-crack.

For pre-cracked specimens, the stress intensity factor K_I is given by

$$K_I = \sigma (\pi a)^{1/2} f(a/w) \quad (1)$$

In which σ is the applied stress, $f(a/w)$ is the geometric correction factor, a is the crack length, and w is the width of the specimen. The functional relationship between $f(a/w)$ and a/w is shown below.

$$f(a/w) = 0.5854(a/w)^3 + 1.099(a/w)^2 + 0.8672(a/w) + 1.049 \quad (2)$$

For a specimen subject to a constant strain rate, the stress intensity factor K_I reaches the critical stress intensity factor K_{IC} at the instant of fracture, and the corresponding flaw size is denoted by a_c , referred to as the critical crack size or the terminal crack size. It follows from Eq. (1) that

$$K_{IC} = \sigma_c (\pi a_c)^{1/2} f(a_c/w) \quad (3)$$

Where σ_c is the critical stress at fracture.

The crack growth rate da/dt has been shown to be a power function of the stress intensity factor K_I , i.e.,

$$da/dt = Q K_I^m \quad (4)$$

in which m and Q are crack growth rate parameters.

When a specimen without pre-crack is subjected to a constant strain rate loading condition, the entire loading history and hence the stress history $\sigma = \sigma(t)$ can be measured, including the critical stress σ_c at the time of fracture, t_c . For a given critical stress intensity factor K_{IC} (material constant), the critical crack size a_c can be computed from Eq. (3). Consequently, the initial flaw size a_0 at $t=0$ can be obtained by integrating Eq. (4), based on the terminal condition (a_c, t_c) and the stress history $\sigma(t)$.

Experimental Analysis

Constant strain rate tests were conducted on specimens with and without pre-crack at a strain rate of 0.067 in/in/min. The critical stress σ_c and the time to failure t_c were determined from the specimen without pre-crack. The crack growth parameters m and Q were determined from the specimens with pre-crack. The results are: $m = 2.084$ and $Q = 9.3325 \times 10^{-7}$ in which the units are force in pound, length in inch, and time in minute. Further, the critical stress intensity factor and the threshold stress intensity factor are $78.3 \text{ psi (in)}^{1/2}$ and $52 \text{ psi (in)}^{1/2}$, respectively. In addition, uniaxial edge-cracked tensile specimens with different initial crack lengths (0 in., 0.1 in., 0.2 in. and 0.3 in.) were tested at four different displacement rates (0.2 in/min, 2 in/min, 20 in/min, and 200 in/min).

Results and Discussion

Typical plots of stress intensity factor versus time and crack length versus time are shown in Figures 1 and 2. In the crack growth analysis, the effect of the threshold stress intensity factor for the onset of crack growth, K_{th} , was not considered. Hence, the flaw size a_0 at $t = 0$ represents the EICS with $K_{th} = 0$. By knowing K_{th} , the time t^* corresponding to K_{th} and the flaw size at t^* , denoted by a^* , can be obtained from Figures 1 and 2. The results of the analysis are shown in Table 1. According to Table 1, it is seen that a_0 and a^* are very close to each other. This indicates that the accuracy of the crack growth model and the developed EICS predictive model is excellent.

In this study, the equivalent initial crack is a hypothetical crack assumed to exist in the material. It characterizes the equivalent effect of an actual initial crack in the material. The equivalent initial crack is not a physically observable initial crack. Therefore, the predicted equivalent initial crack must be justified using applicable test data. In other words, the predicted EICS needs to be verified experimentally. To achieve this goal, uniaxial edge-cracked tensile specimens with different initial crack lengths (0 in., 0.1 in., 0.2 in. and 0.3 in.) were tested at four different displacement rates (0.2 in/min, 2 in/min, 20 in/min, and 200 in/min). The tests results, plotted the maximum stress σ_{max} versus the corresponding time t_{max} , are shown in Figure 3. By shifting the un-precracked specimen data vertically downward until they superpose upon those of the pre-cracked specimen, we can obtain an estimate for the initial flaw size in the un-precracked specimen. The dashed lines in Figure 3 represent the vertically shifted curves. According to Figure 3, the initial crack size in the un-precracked specimen is approximately equal to 0.1 in. which compares well with the predicted value of 0.125 in.

In addition to determining the EICS, the statistical distribution function of the EICS is also determined. The distribution of initial flaw size is a measure of the initial quality of the material and it provides information for determining the threshold crack size for nondestructive inspection. Also, the determination of the size of the initial flaw in the particulate composite material may provide information regarding the applicability of using fracture mechanics to predict the crack growth behavior in the material.

In this study, four statistical distribution functions, (1) normal distribution, (2) two-parameter Lognormal distribution, (3) two-parameter Weibull distribution and (4) second asymptotic distribution of maximum values, were considered. Typical plots of the statistical distribution of the second asymptotic distribution of maximum value for a_0 and a_c are shown in Figures 4 and 5. For a comparison purpose, experimental data, shown as circles, are also included in these figures. It is seen that the second asymptotic distribution of maximum value fits the experimental data very well. In addition, the goodness of fit for different distributions was conducted using the Kolomogorov-Smirov test. The results also indicate that the second asymptotic distribution of the maximum value has the best fit for the distribution of a_0 and a_c .

Conclusion

In this study, a method is developed to predict the initial crack length in a particulate composite material subjected to a constant strain rate loading condition. By comparing the estimated values of a_0 and a^* , obtained from analytical and experimental analyses, the validity of the proposed technique is verified. In addition, the results of statistical analyses indicate that a_0 and a^* follow the second asymptotic distribution of maximum value.

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Table 1. Summary of Flaw Sizes

Test Specimen	Thickness, B [in.]	Width, W [in.]	a_0 [in.]	a^* [in.]	t^* [min.]	a_c [in.]
MM5-1b.mad	0.198	1.000	0.1221	0.1263	3.0755	0.1415
MM2-2.mad	N/A	N/A	0.1279	0.1320	2.9113	0.1456

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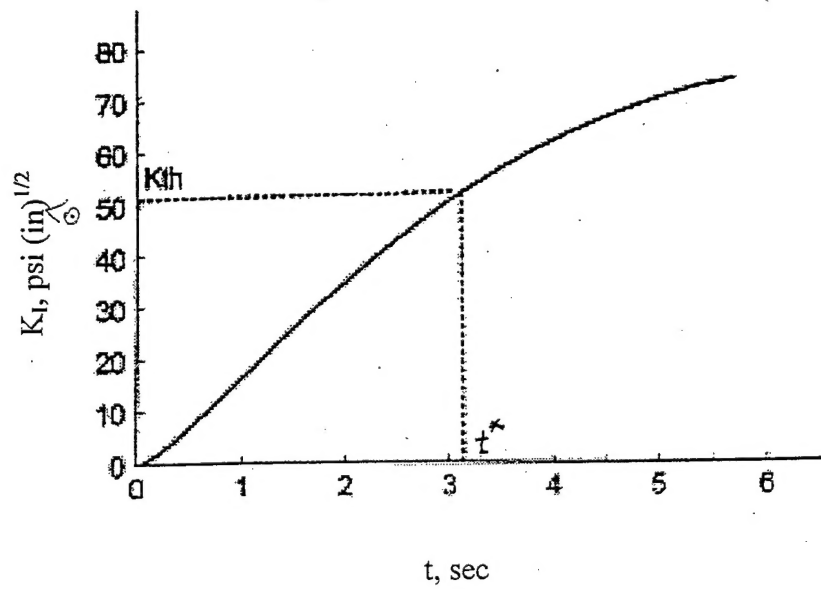


Fig. 1 Stress intensity factor K_I versus time t

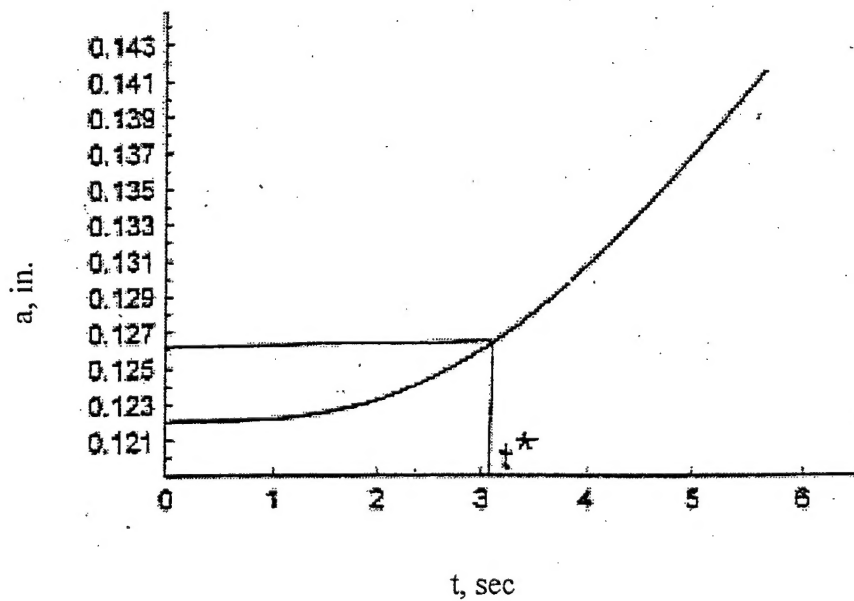


Fig. 2 Crack length a versus time t .

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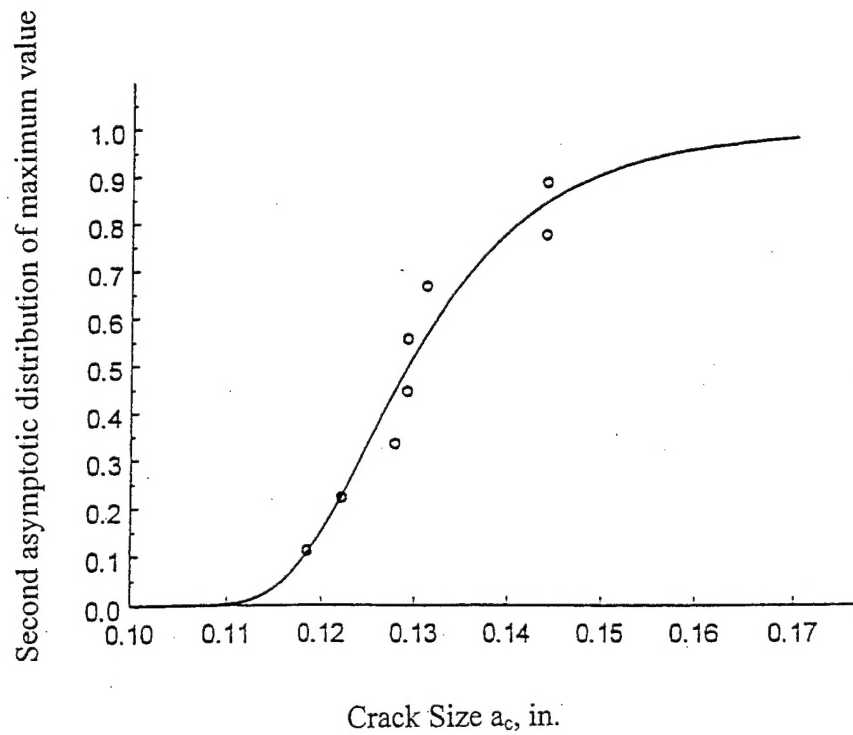


Fig. 3 Second asymptotic distribution of maximum value
 p -plot for a_c .
 (lowercase)